Mixing, Internal Waves and Mesoscale Dynamics in the East China Sea

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LONG TERM GOAL

The long-term goal of our research program is to better understand and quantify the relationships between mesoscale dynamics, internal waves, turbulence and topographic features of shallow, tidally-affected regions of oceans.

OBJECTIVES

The objectives of the project during 2009 were:

(i) to analyze the intermittency of turbulence in a tidal bottom boundary layer (TBBL) on a shallow shelf in the western (Chinese) sector of the East China Sea (ECS),

(ii) to continue investigations on the turbulent kinetic energy (TKE) dissipation rate very near the ocean floor, in particular the role of small-scale local bathymetry in small-scale mixing. The emphasis was on the area influenced by Changjiang (Yangtze River) Diluted Water (CDW). , and

(iii) to study mixing efficiency in stratified flows based on data available from atmospheric and oceanic field campaigns.

APPROACH

Analysis of field data collected in 2005 and 2006 in ECS during the research cruises of the Ocean University of China (OUC) and Korea Ocean Research and Development Institute (KORDI).

WORK COMPLETED

Study of the near-bottom turbulence in Chinese sector of ECS: friction velocity, dissipation rate, and intermittency.

Study of mixing efficiency in stratified flows.

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RESULTS

A. TURBULENCE INTERMITTENCY IN A TIDAL FLOW NEAR THE SEAFLOOR ON A SHALLOW SHELF OF THE EAST CHINA SEA

As has already been reported [*Lozovatsky et al*. 2008 a,b], our collaborator and subcontractor, OUC, conducted hydrophysical measurements in the ECS in the close proximity (1.2 km) to the shore of the Jiaozhou Bay (λ = 36.04°N, φ = 120.32°E). The higher-order (q) structure functions of vertical velocity fluctuations

$$\left\langle \Delta w_r^q \right\rangle = C_q \left(\varepsilon_r r\right)^{\xi(q)}, \tag{1}$$

(transverse structure functions or TSF) were employed to study the characteristics of turbulence intermittency in a reversing tidal flow on a 19-m deep shallow shelf of ECS. Eq.(1) represents scaling assumption of a refined similarity hypothesis [*Kolmogorov* 1962; *Obukhov* 1962] that accounts for fluctuations of the dissipation rate ε at the scale r of locally isotropic turbulence in inertial-convective and viscous dissipative spectral subranges. A classical lognormal single parameter (μ) model

$$\xi(q) \equiv \xi_{lm} = \frac{q}{3} - \frac{\mu}{18}\left(q^2 - 3q\right) \tag{2}$$

for intermittency and a universal multifractal approach (specifically, the two-parameter (C_1 and α) log-Levy model)

$$\xi(q) \equiv \xi_{fm} = \frac{q}{3} - \frac{C_1}{\alpha - 1}\left[\left(\frac{q}{3}\right)^{\alpha} - \frac{q}{3}\right], \tag{3}$$

were employed to analyze the TSF exponent $\xi(q)$ in tidally-driven turbulent boundary-layer and the parameters μ, C_1 and α were estimated. Measurements from a downward-looking bottom-mounted ADV, positioned 0.45 m above the sea floor were utilized, and the data spanned two semidiurnal tidal cycles.. To analyze the intermittency in tidal boundary layer turbulence, 25-hour records of the ADV current components were subdivided into 44 segments. Each segment contained 2^{15} = 32628 individual samples (time interval ~ 34 min), which was relatively long to provide sufficient multiplicative averaging of higher-order TSF calculations and to minimize errors to an acceptable level. The mean TKE dissipation rate $\tilde{\varepsilon}_{nb}$ at each segment i was estimated from the inertial subrange of the frequency counterpart of the Kolmogorov wave number spectra. Taylor's "frozen turbulence" hypothesis was employed to transform $w(t)$ at each segment to the spatial series $w(x)$. The applicability of Taylor's hypothesis was tested by calculating the ratio $rms_i\left(w'\right)/U_i$; it never exceeded 2.5% at segments close to high and low tides (minimum advecting velocity) and mostly was below 1%. Possible impacts of Taylor hypothesis on TSF exponents were carefully scrutinized.

During energetic flooding tidal phases (high integral Reynolds numbers Re_{int}), the parameters of intermittency models approached the mean values of $\tilde{\mu} \approx 0.24$, $\tilde{C}_1 \approx 0.15$, and $\tilde{\alpha} \approx 1.5$, which are accepted as the universal values for fully-developed turbulence at high *Re*. With the decrease of advection velocity, and therefore *Re*, μ and C_1 increased up to $\mu \approx 0.5$ - 0.6 and $C_1 \approx 0.25$ - 0.35, but α decreased to about 1.4 (Fig. 1).

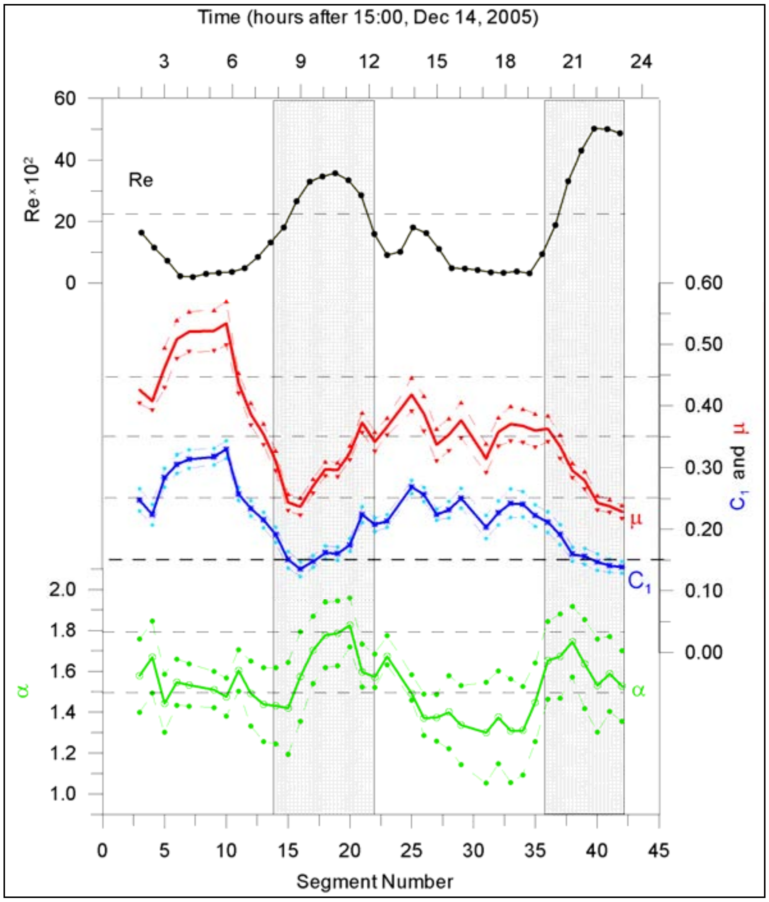

Fig. 1. The parameters of multifractal (Eq. 3, C_1 and α) and log-normal (Eq. 2, μ) intermittency models shown with 95% confidence bounds. The turbulent integral (Re) Reynolds number is mainly in phase with α and out of phase with C_1 and μ. Two periods of flooding currents with the highest Re_t recorded are highlighted.

The dependence of μ, C_1, and α on internal flow parameters, such as the microscale Reynolds number $R_{\lambda w}$, which is a variant of $R_\lambda = rms(u')\lambda/\nu$, is presented in Fig. 2. Despite high scatter, the data show a general increase of μ and C_1 with decreasing $R_{\lambda w}$ (Fig. 2 a,b). The best least-square power trends are given with 95% confidence bounds and coefficients of determination r^2. The empirical functions so obtained are

$$\mu = 0.23 + R_{\lambda w}^{-0.8} \quad \text{and} \quad C_1 = 0.13 + R_{\lambda w}^{-0.9}, \tag{4}$$

implying that μ and C_1 have similar dependencies on $R_{\lambda w}$, attaining asymptotic values of $\mu^o = 0.23$ and $C_1^o = 0.13$ at high $R_{\lambda w} > 500\text{-}700$.

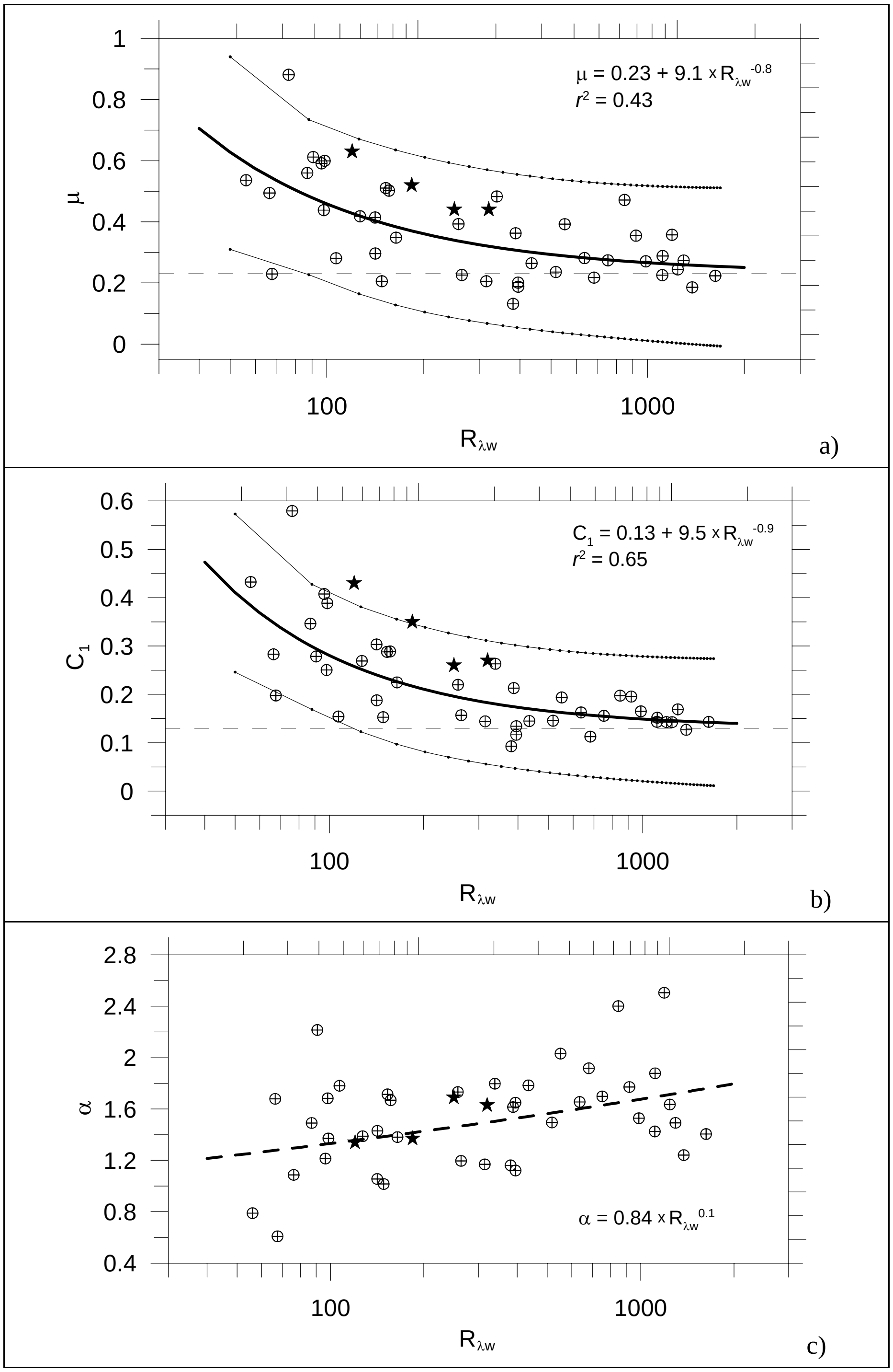

Fig. 2. The dependencies of intermittency parameters μ, C_1 and α on the local turbulent Reynolds number $R_{\lambda w}$. The least-squared fits with 95% lower and upper confident bounds (for μ and C_1) are shown. The laboratory data of Hao et al., [2008] are shown by stars.

Both estimates are close to the universal values of $\hat{\mu}$ and $\hat{C}_1$ expected from turbulence intermittency models at high Reynolds numbers. A weak (statistically insignificant) dependence of α on $R_{\lambda w}$ is shown in Fig. 2c. The mean value $\tilde{\alpha} = 1.53 \pm 0.39$, however, matches well with the "universal" $\hat{\alpha} = 1.5 - 1.55$ cited by *Seuront et al.* [2005] for log-Levy multifractal intermittency model. It should be noted that the analysis here was based on TSF, which could be compared with the laboratory data of *Hao et al*. [2008], as shown in Fig. 2 by stars.

The results explain the reported disparities between the smaller "universal" values of intermittency parameters μ and C_1 (mostly measured in laboratory and atmospheric high-Reynolds number flows) and those (μ = 0.4 - 0.5) reported for oceanic stratified turbulence in the pycnocline, which is associated with relatively low local Reynolds numbers $R_{\lambda w}$.

The scaling exponents $\xi(2)$ of the second order TSF, relative to the third order SF, was also found to be a decreasing function of $R_{\lambda w}$, approaching the classical value of 2/3 at very high $R_{\lambda w}$. A larger departure from the universal turbulent regime at lower Reynolds numbers could be attributed to the higher anisotropy and associated intermittency of under-developed turbulence.

B. THE DISSIPATION RATE NEAR THE SEAFLOOR ON A TIDAL SHELF IN THE EAST CHINA SEA

The profiles of the TKE dissipation rate were measured in the Changjiang (Yangtze River) Diluted Water of the East China Sea (CDW region: λ = 30°49'N, φ = 122°56'E; the mean depth H_B = 38 m) by a microstructure profiler (MSS) during two semidiurnal cycles. Basic characteristics of tidal flow, stratification, and microstructure in the region were analyzed and reported by *Lozovatsky and Fernando*[2008]. In 2009, we continued investigations of CDW regional dynamics, focusing on near-bottom turbulence. The time variation of the velocity vector (its magnitude U and direction ϕ) at ζ = 0.3 mab are shown in Fig. 3, where ζ is a distance in meters above the bottom.

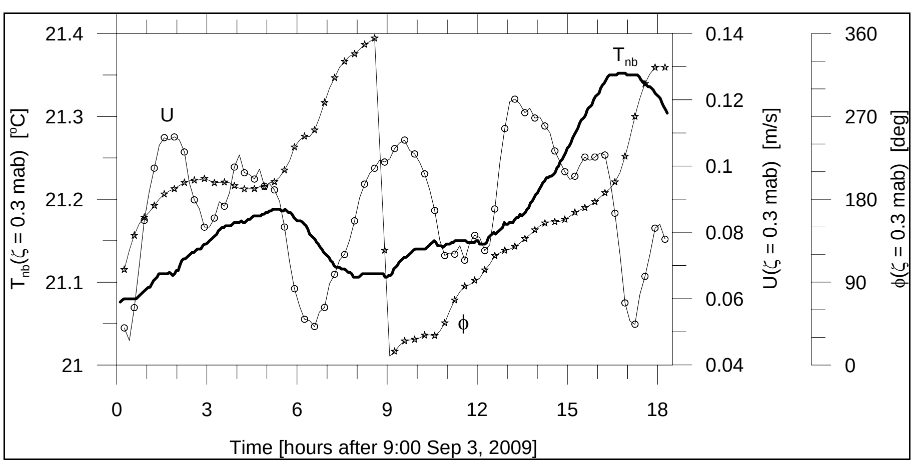

Fig. 3. The near-bottom (ζ = 0.3 mab) temperature T_{nb}, direction ϕ, and magnitude U of the mean current.

The magnitude of the velocity vector was affected by oscillations having a quarter diurnal period (the minimums at t ~ 6.6, 11.8, and 17.3 hrs) induced by irregular semidiurnal (12.42 hr) barotropic tide. The current direction $\phi(t)$ exhibits complete 360^{o} rotation during approximately 12 hours (ϕ = 123^{o}, for example, at t = 0.4 and 12.8 hr), which was also affected by higher harmonics (for example, ϕ = 270^{o} at t = 6.8 and 17.3 hr or ϕ = 180^{o} at t = 1.4 and 16.1 hr).

The MSS profiles $\varepsilon_{mc}(\zeta)$ obtained in this rotating tidal flow were compared with the dissipation rate profiles $\varepsilon_{wl}(\zeta)$ calculated using (i) the law of the wall and (ii) the estimates of friction velocity u_* deduced from logarithmic approximation of the ADCP velocity profiles very near to the seafloor (ζ = 0.04 – 0.4 mab) while ensuring the skin-layer accuracy for u_*. The sensitivity of u_* to various time averaging periods was also tested; 30 min averaging provided the highest coefficient of determination for the log-layer fits, while ensuring reasonable stationarity of tidal flow over the averaging period. During the tidal cycle, u_* varied in the range $(1-7)\times10^{-3}$ m/s. In general, law of the wall dissipation profiles befittingly intersected with the MSS profiles at ζ = 2 – 5 mab, suggesting the applicability of the law of the wall in shallow tidal-affected waters at the time scales of about 30 min (see examples in Fig. 4).

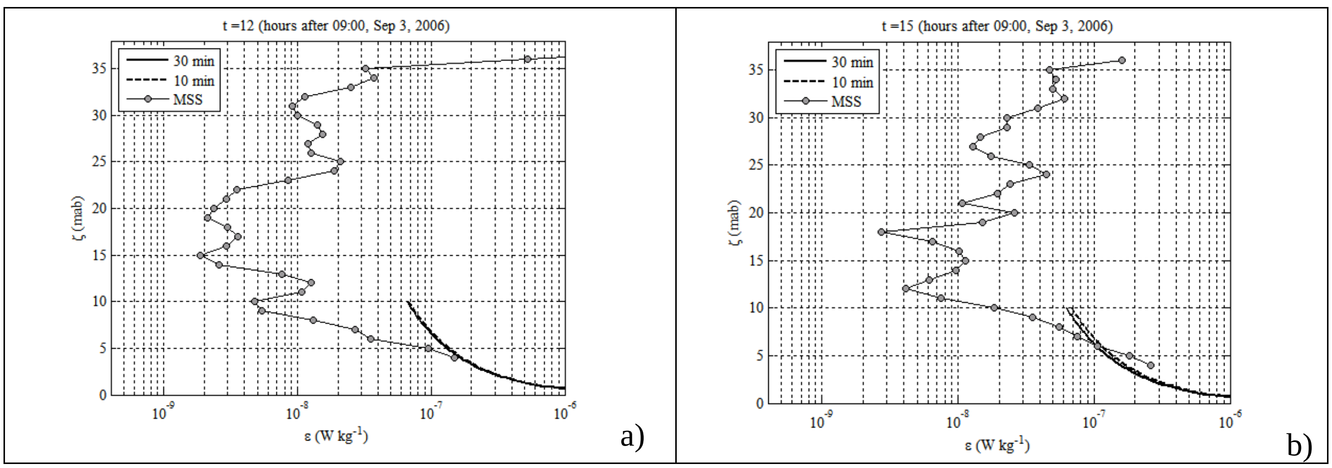

Fig. 4. The MMS dissipation profiles $\varepsilon_{mc}(\zeta)$ and the law-of-the-wall profiles $\varepsilon_b(\zeta)$ for the across-slope eastern (a) and along-slope southern (b) flow (τ_{avr} = 30 and 10 min).

When turbulence in the bottom boundary layer is influenced, in addition to local friction, by other external sources (lateral advection, convection, internal wave generation), the level of the dissipation can be substantially higher compared to $\varepsilon_{wl}(\zeta)$. The local bathymetry also appears to play a role in the enhancement of $\varepsilon_{mc}(\zeta)$ compared to $\varepsilon_{wl}(\zeta)$ in the lower 7 – 10 m of the water column during the upslope phase of the westerly directed tidal current in the CDW region (Fig. 5).

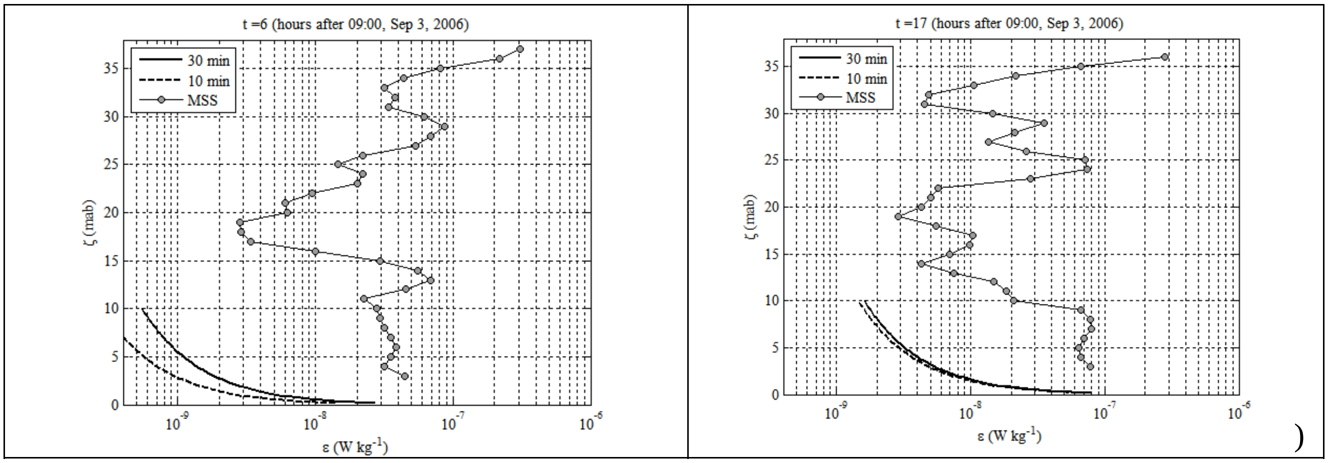

Fig. 5. The MMS dissipation profiles $\varepsilon_{mc}(\zeta)$ and the law-of-the-wall profiles $\varepsilon_b(\zeta)$ for the across-slope western flow influenced by a turbulent wake behind local seamount.(τ_{avr} = 30 and 10 min).

It is hypothesized that the turbulence generated at the summit and flanks of a small seamount to the east of the observational site was advected onshore, providing an increased level of the dissipation rate in the BBL compared to regular background tidal-induced wall turbulence.

IMPACT/APPLICATION

Our research program has been enormously strengthened by the international collaboration provided by the grant. A joint paper with the Chinese colleagues has been published in 2009 in the Journal of Marine Systems and another paper on turbulence intermittency is under revision in the Journal of Geophysical Research. A paper on the near-bottom turbulence in the CDW region of ECS is ready for submission to the journal of Continental Shelf Research. A complimentary research effort on mixing efficiency in stratified flows generated a paper that is being submitted to the Journal of Physical Oceanography. The PI Lozovatsky visited KORDI in August, and had productive discussions on the analysis of data obtained recently by the Korean collaborators. He will be visiting China (Xiamen University) in October to discuss future research in the East and South China Seas in collaboration with Chinese oceanographers.

TRANSITIONS

None

RELATED PROJECTS

The Co-P.I. Fernando is involved in another ONR funded project dealing with laboratory investigations of submarine wakes in stratified fluid funded by the ONR turbulence program.

PUBLICATIONS

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